Introducing the Greenhouse Effect

EES 3310/5310

Global Climate Change

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Class #4: Monday, Feb. 1 2021

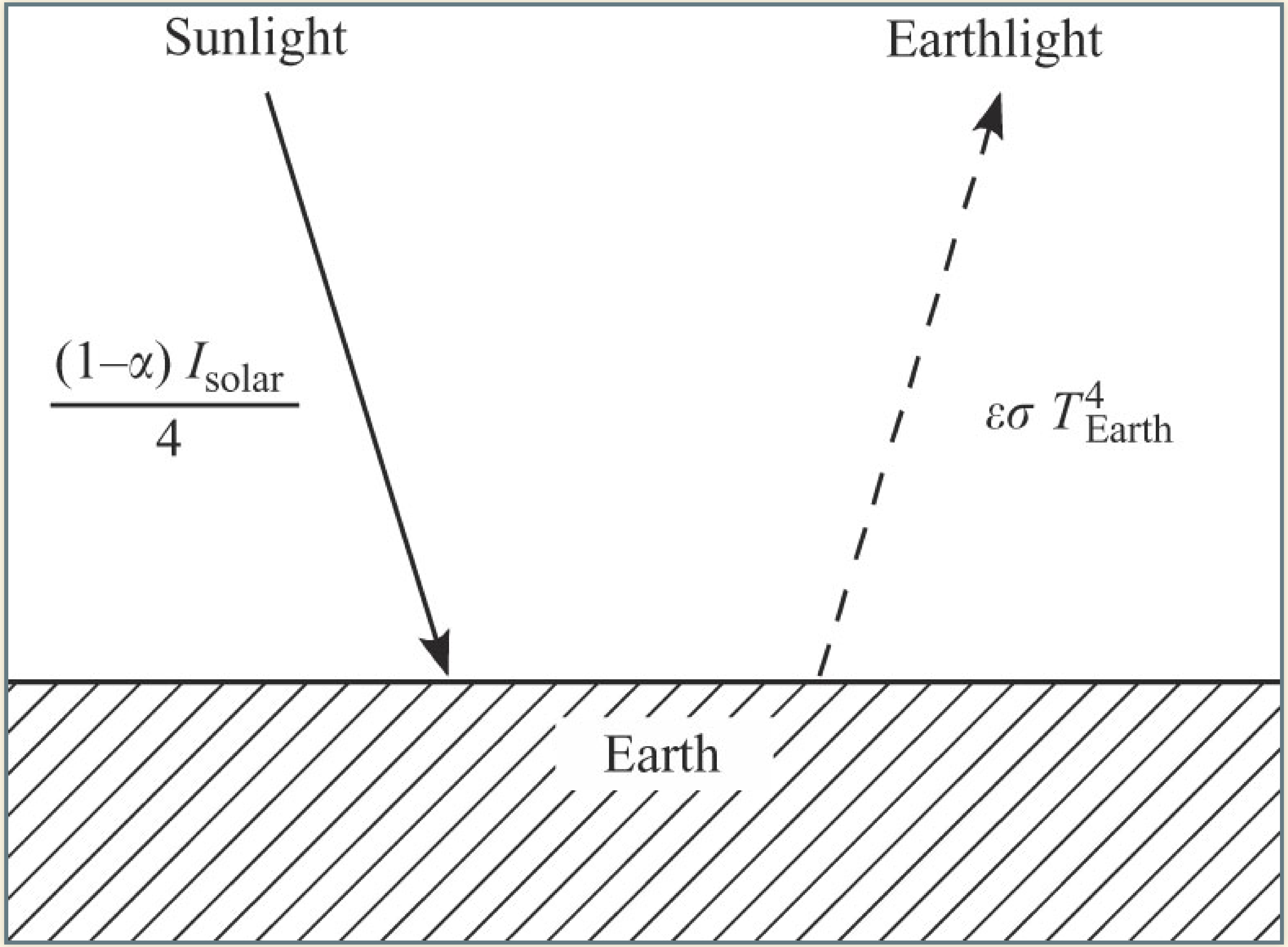
Basic Principles from Friday

- **Steady temperature means:**
  - $\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$
- **Heat in:**
  - Sunlight (**shortwave**)
  - Does not depend on temperature
- **Heat out:**
  - Emitted radiation (**longwave**)
  - Depends on temperature
- If $\text{Heat}_{\text{out}} \neq \text{Heat}_{\text{in}}$,
  - Temperature rises or falls until

$$\text{Heat}_{\text{out}} = \text{Heat}_{\text{in}}$$

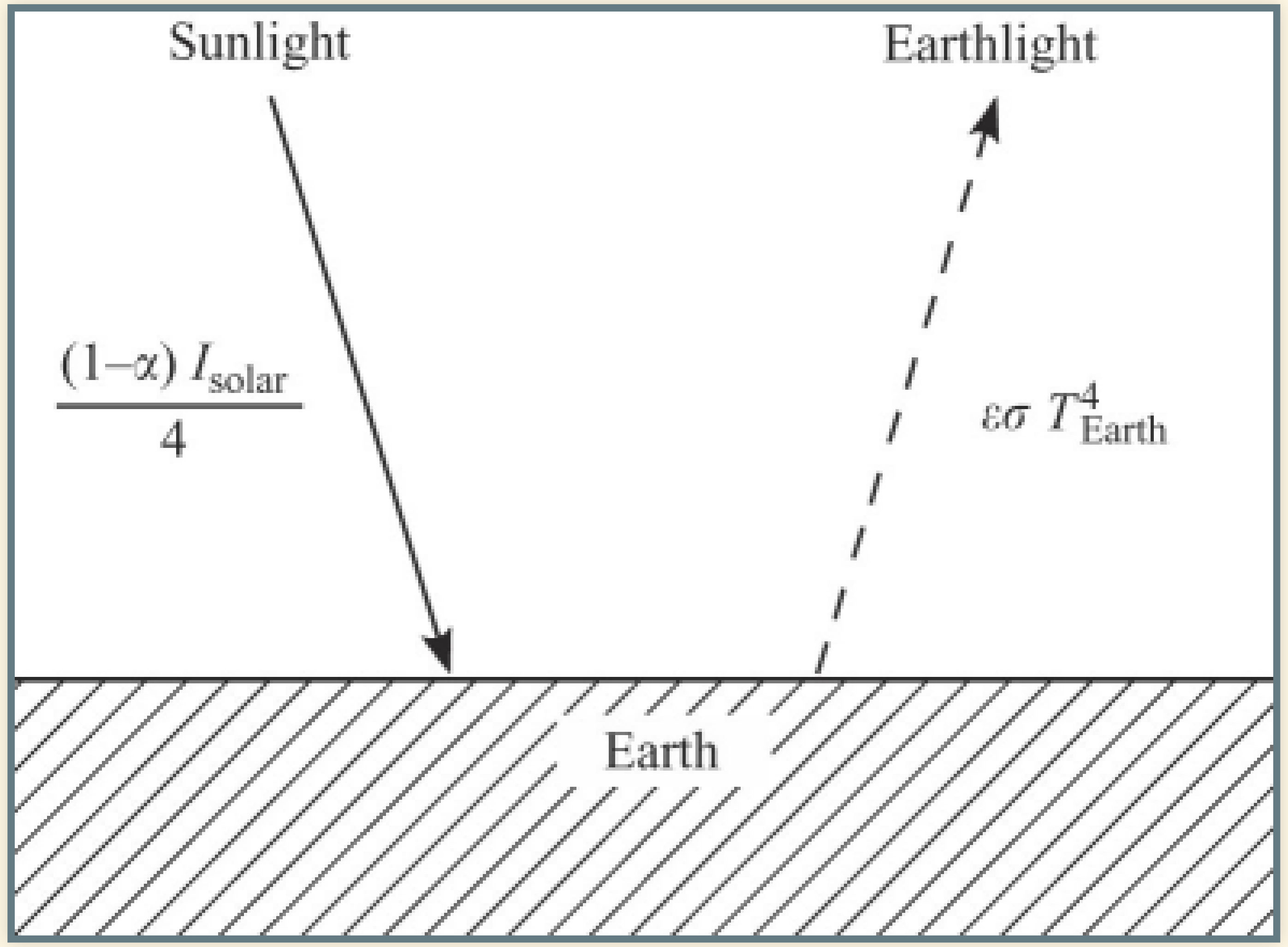
Temperature of the Earth

Bare-Rock Model: No Atmosphere



A subtle point...

- Emissivity ε is fraction absorbed
- Albedo α is fraction reflected
- For an opaque surface, $\alpha + \varepsilon = 1$
- So how is $\alpha = 0.30$ and $\varepsilon = 1.00$?
- α & ε are different for shortwave & longwave.
- Shortwave: $\alpha = 0.30$, $\varepsilon = 0.70$
- Longwave: $\alpha = 0.00$, $\varepsilon = 1.00$



Temperature of Earth (Bare Rock Model)

1. $F_{\text{out}} = F_{\text{in}}$ (Heat flux balances)
2. On average,

$$F_{\text{in}} = \frac{(1-\alpha)}{4} I_{\text{solar}}$$

3. $F_{\text{out}} = \varepsilon \sigma T^4$.
4. Solve for T:

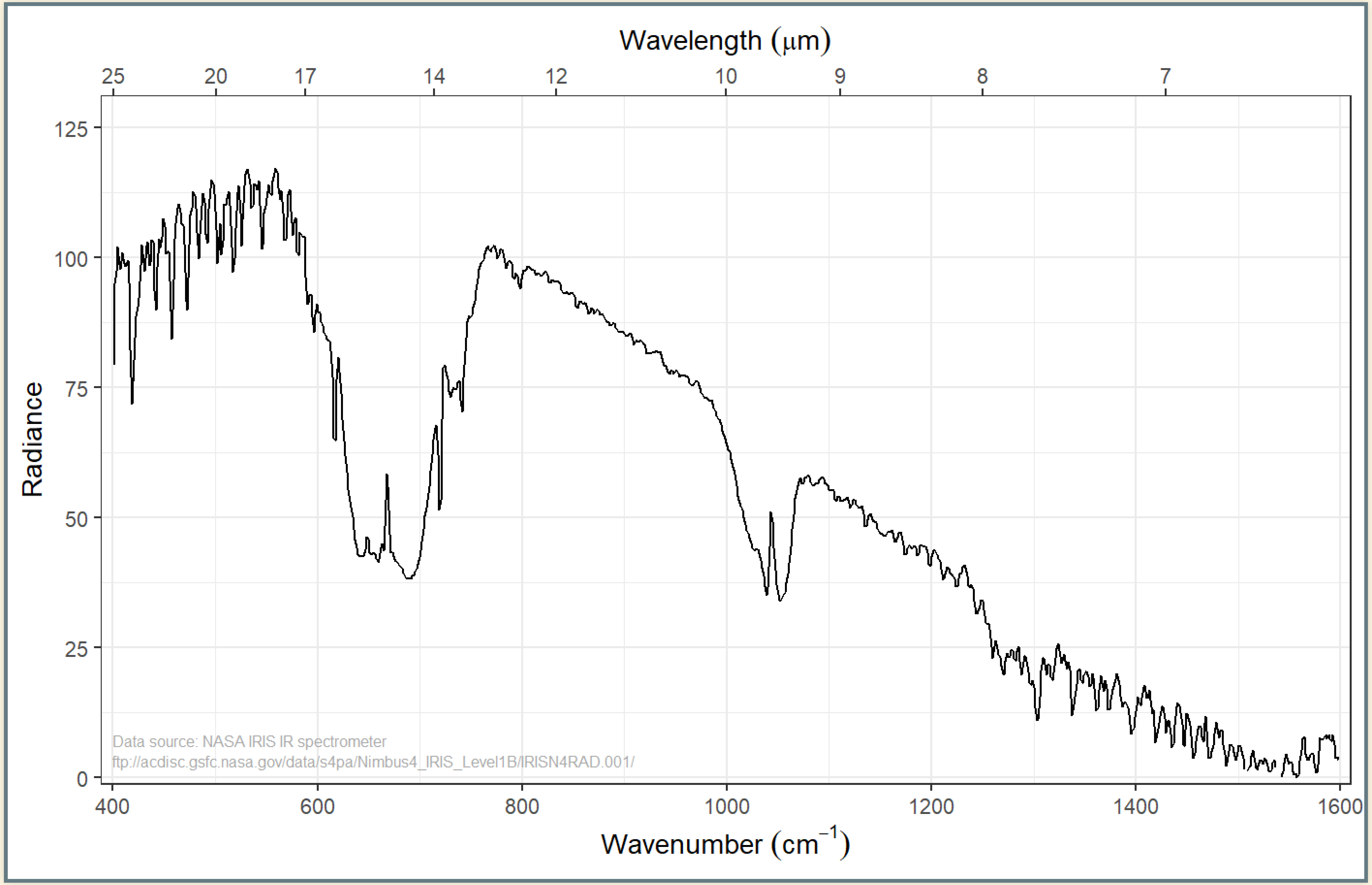
$$T = \sqrt[4]{\frac{(1-\alpha) I_{\text{solar}}}{4 \varepsilon \sigma}}$$

$$\begin{aligned} I_{\text{solar}} &= 1350\ \mathrm{W/m^2} \\ \alpha &= 0.30 \\ \varepsilon &= 1 \\ \sigma &= 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}} \\ T &= 254\ \mathrm{K} = -19^\circ\mathrm{C} = -2^\circ\mathrm{F} \end{aligned}$$

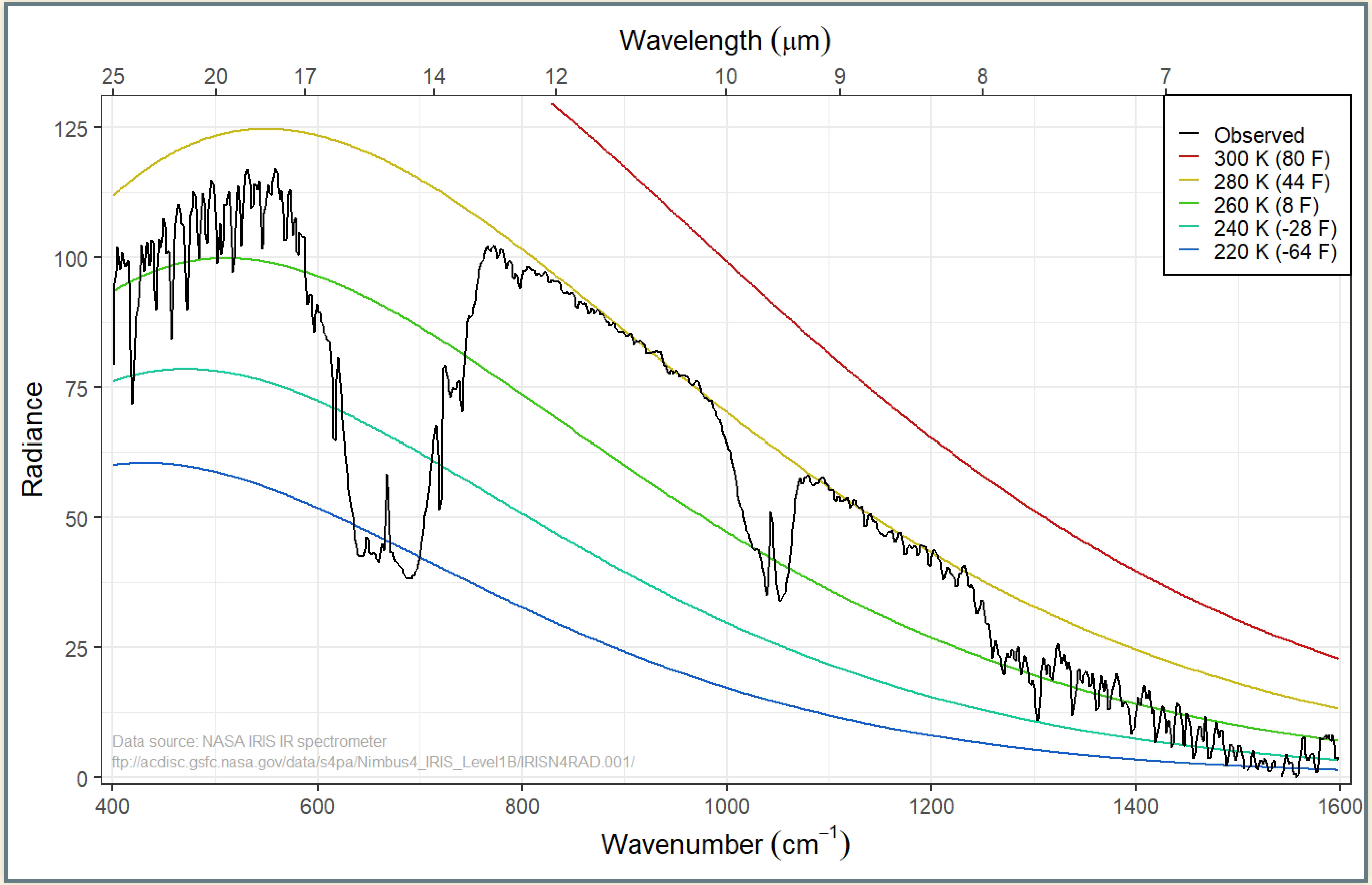
Terrestrial Planets

	Earth	**Mars**	**Venus**
Distance from sun	1 AU	1.5 AU	0.72 AU
$1/\mathrm{Distance}^2$	1.00	0.44	1.9
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
Albedo	0.30	0.17	0.71
$T_{\mathrm{bare\ rock}}$	254 K (-2°F)	216 K (-70°F)	240 K (-27°F)
T_{surface}	295 K (71°F)	240 K (-28°F)	700 K (800°F)
Δ_T	41 K (74°F)	24 K (42°F)	460 K (828°F)

Oops! We forgot the atmosphere!

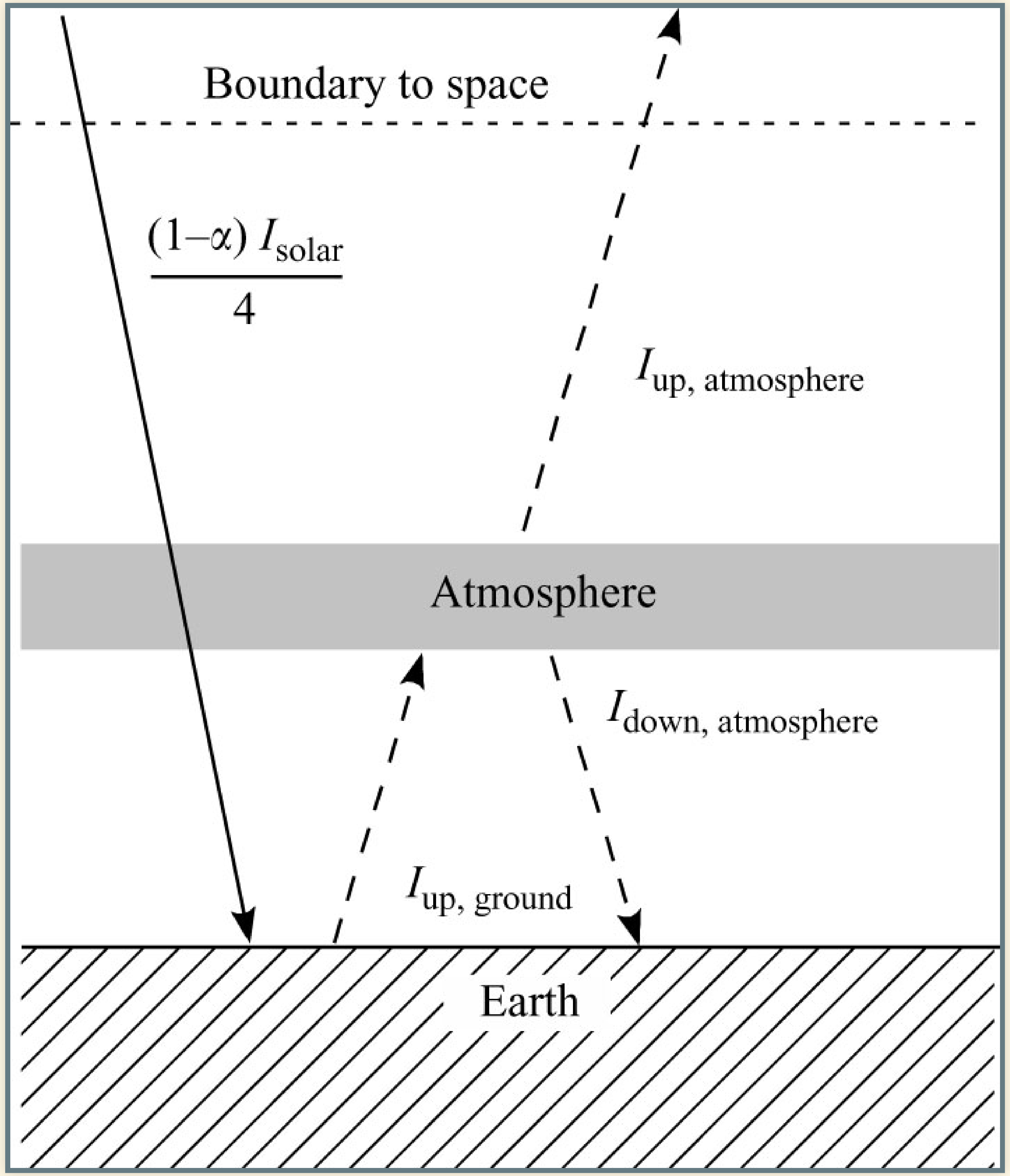


Does Earth look like a blackbody?



One-Layer Model of the Greenhouse Effect

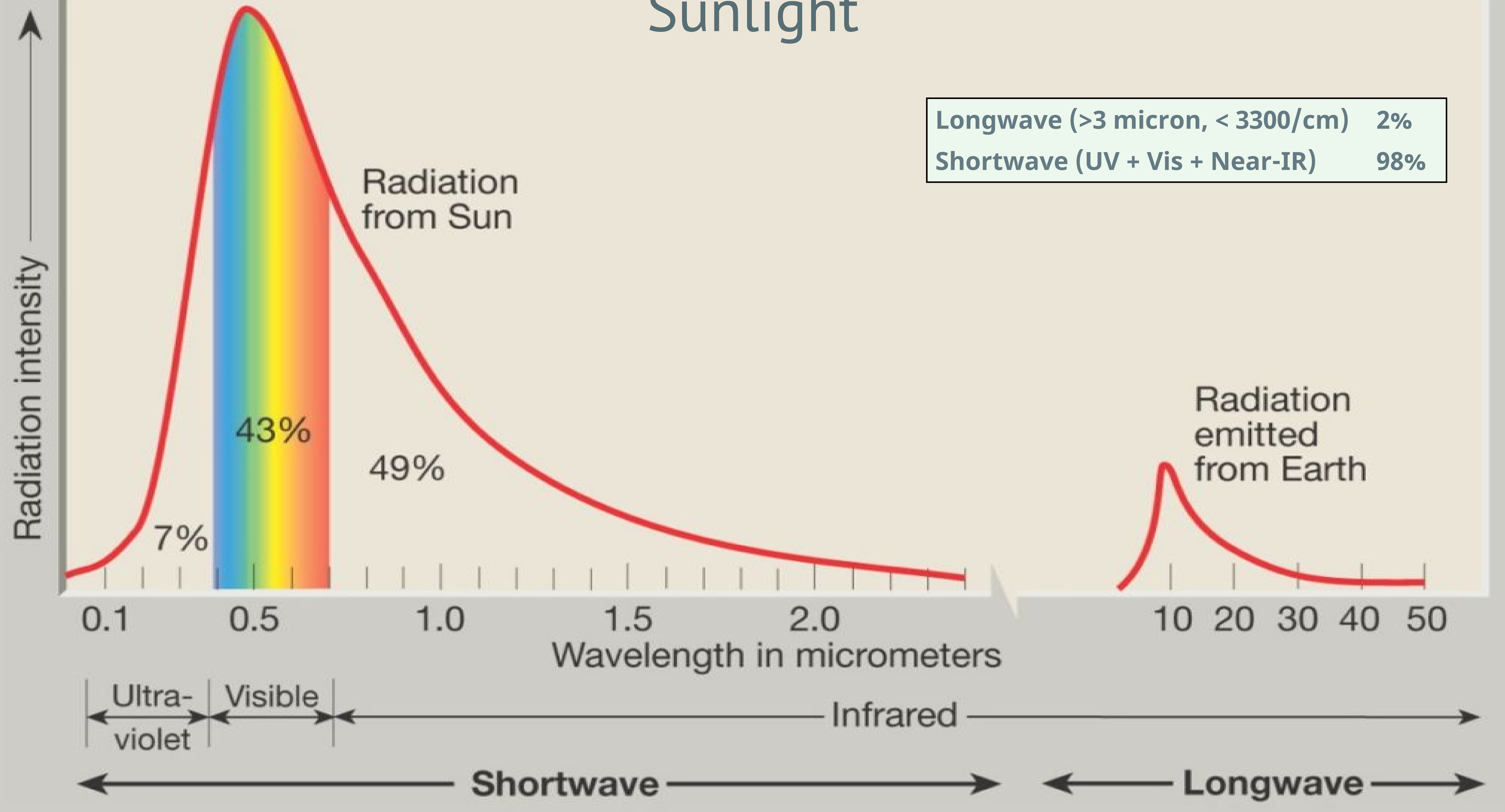
Layer Model



Boundary to space
$\frac{(1-\alpha)\, I_{solar}}{4}$
$I_{up,\ atmosphere}$
Atmosphere
$I_{down,\ atmosphere}$
$I_{up,\ ground}$
Earth

Sunlight

Longwave (>3 micron, < 3300/cm)	2%
Shortwave (UV + Vis + Near-IR)	98%



Atmosphere

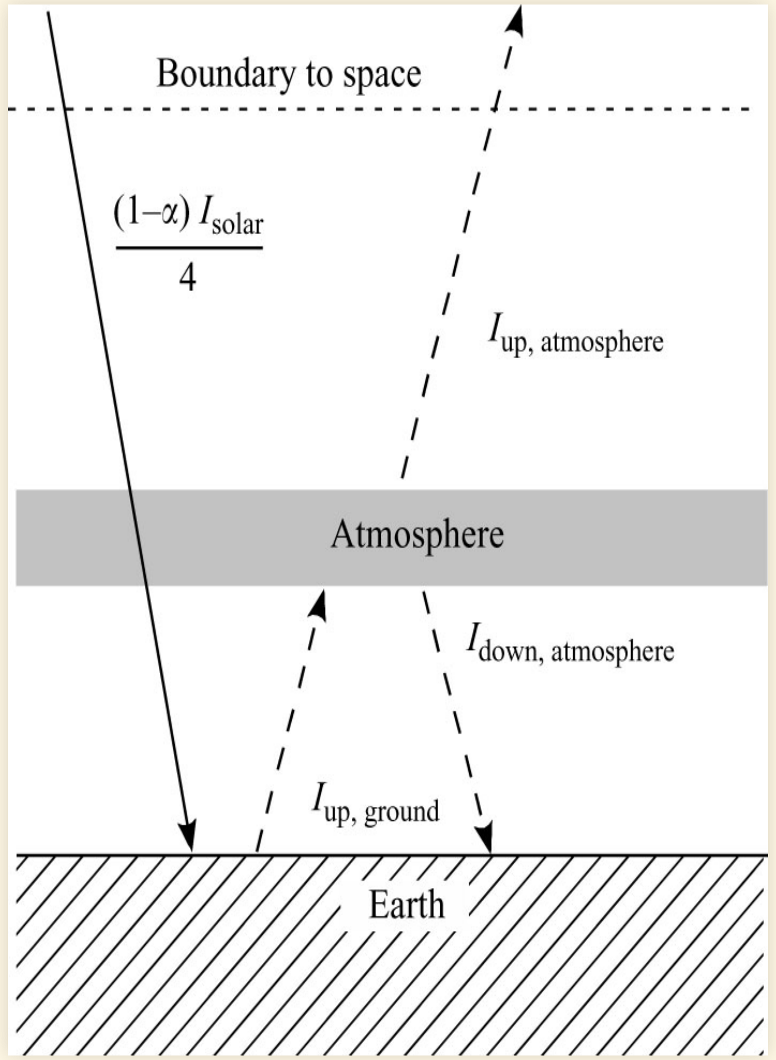
Make **simplifying assumptions**:

- Perfectly **transparent** to **shortwave** light
  - Like a pane of glass: $\varepsilon = 0$
- Perfectly **opaque** to **longwave** light
  - Like a blackbody: $\varepsilon = 1$

Anything that
transmits most shortwave
and
absorbs most longwave
is a greenhouse gas

Balance of energy for earth system

- Always start analyzing from the top down
  - Look at energy balance at the boundary to space, above the top of the atmosphere.



Balance of energy for earth system

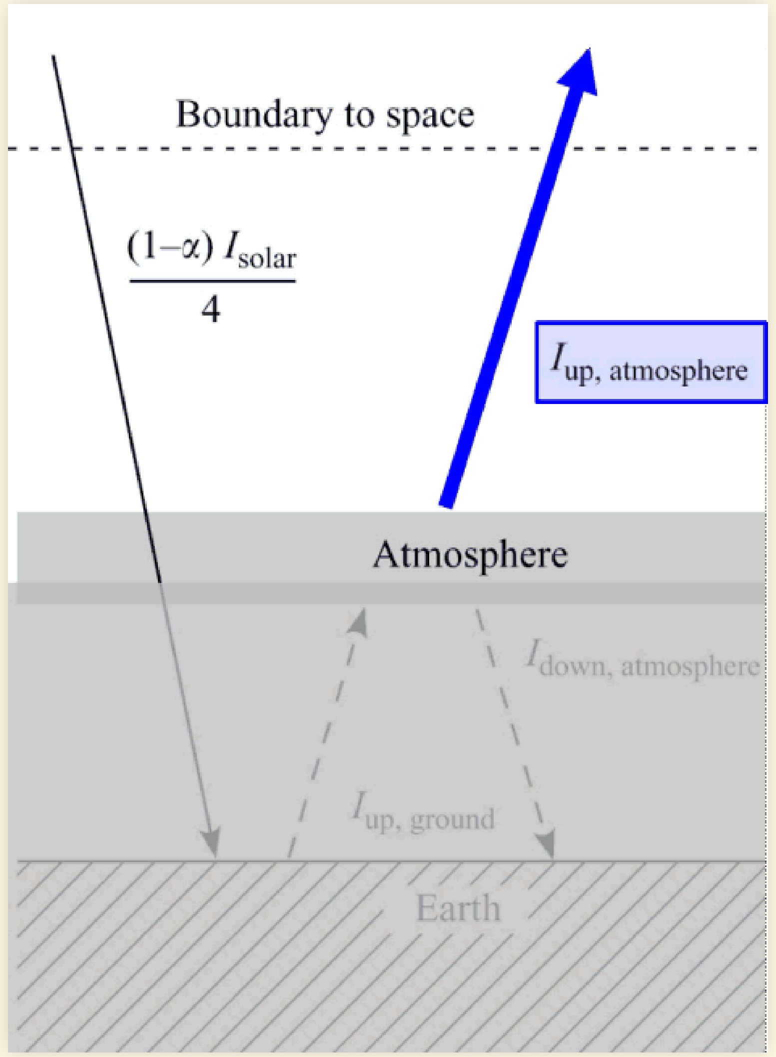
- At top of atmosphere: $F_{\text{out}} = F_{\text{in}}$

$$I_{\text{up, atmos}} = I_{\text{in}} \quad \text{(intensity of absorbed sunlight)}$$

$$\varepsilon\sigma T_{\text{atmos}}^4 = \frac{(1-\alpha) I_{\text{solar}}}{4}$$

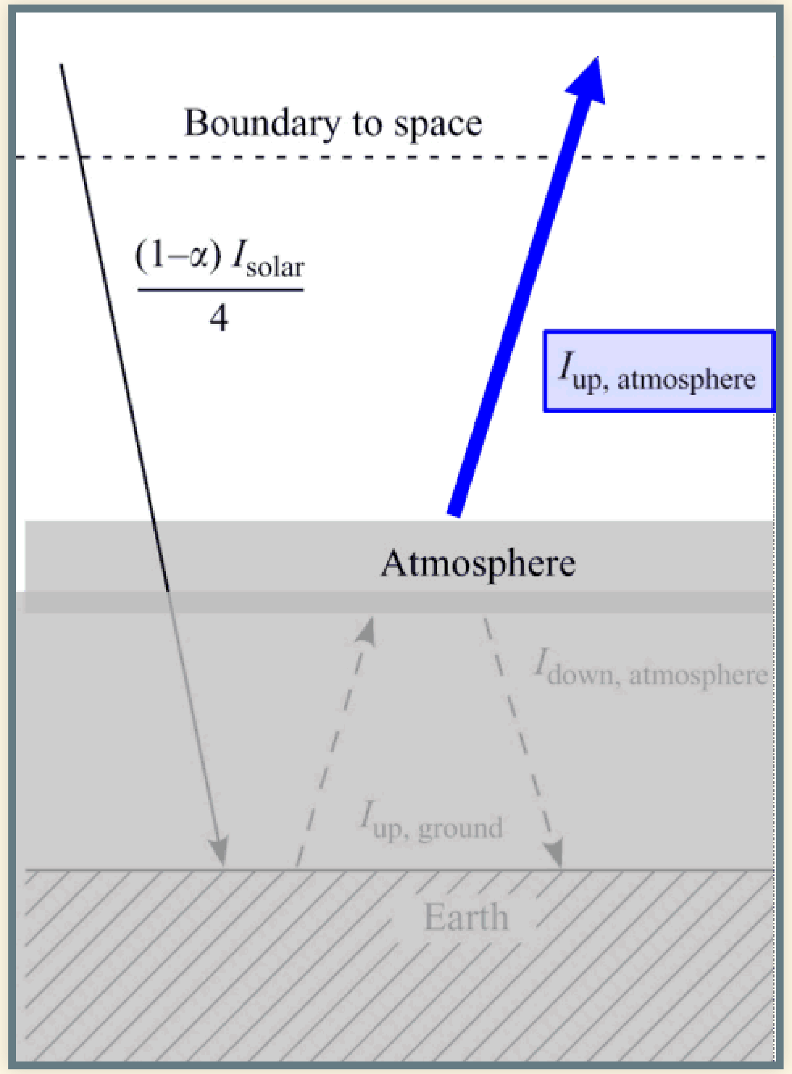
- Aha! We can find T_{atmos}!

$$T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\, I_{\text{solar}}}{4\varepsilon\sigma}}$$



Balance of energy for earth system

$$T_{\text{atmos}} = \sqrt[4]{\frac{(1-\alpha)\, I_{\text{solar}}}{4\varepsilon\sigma}}$$

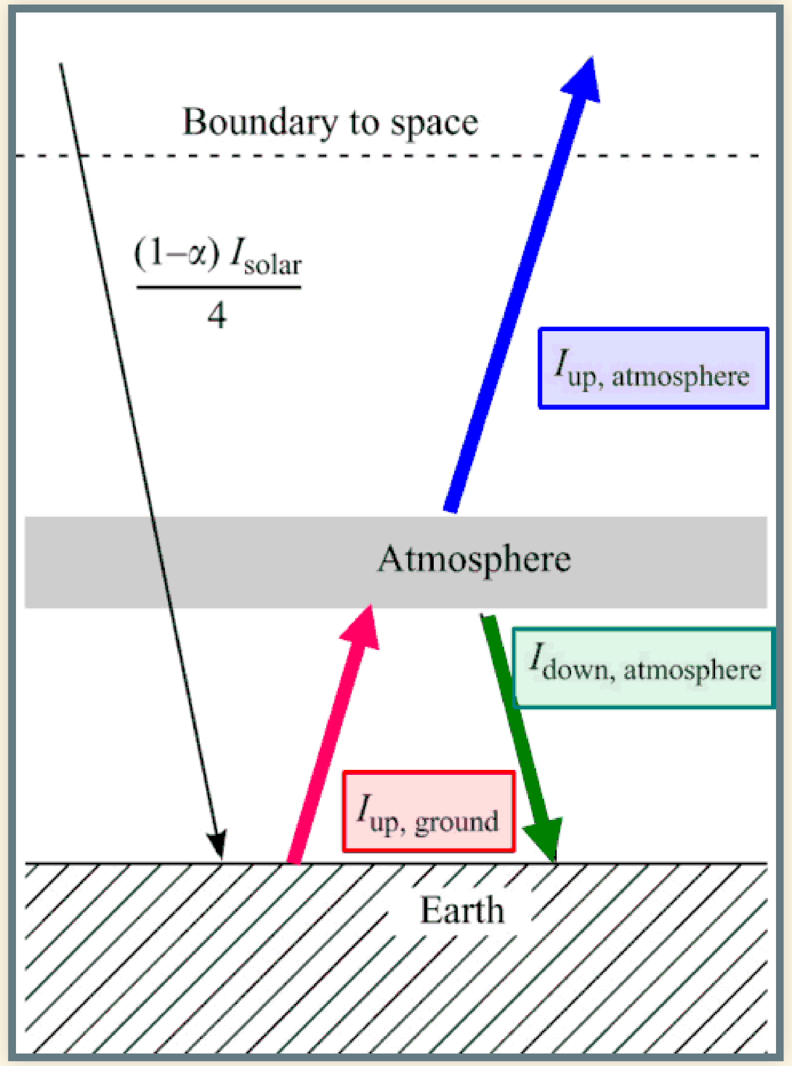


- Just like bare rock model!
- We call this the **skin temperature**

Balance of energy for atmosphere

Atmosphere: $\text{Heat}_{\text{in}} = \text{Heat}_{\text{out}}$

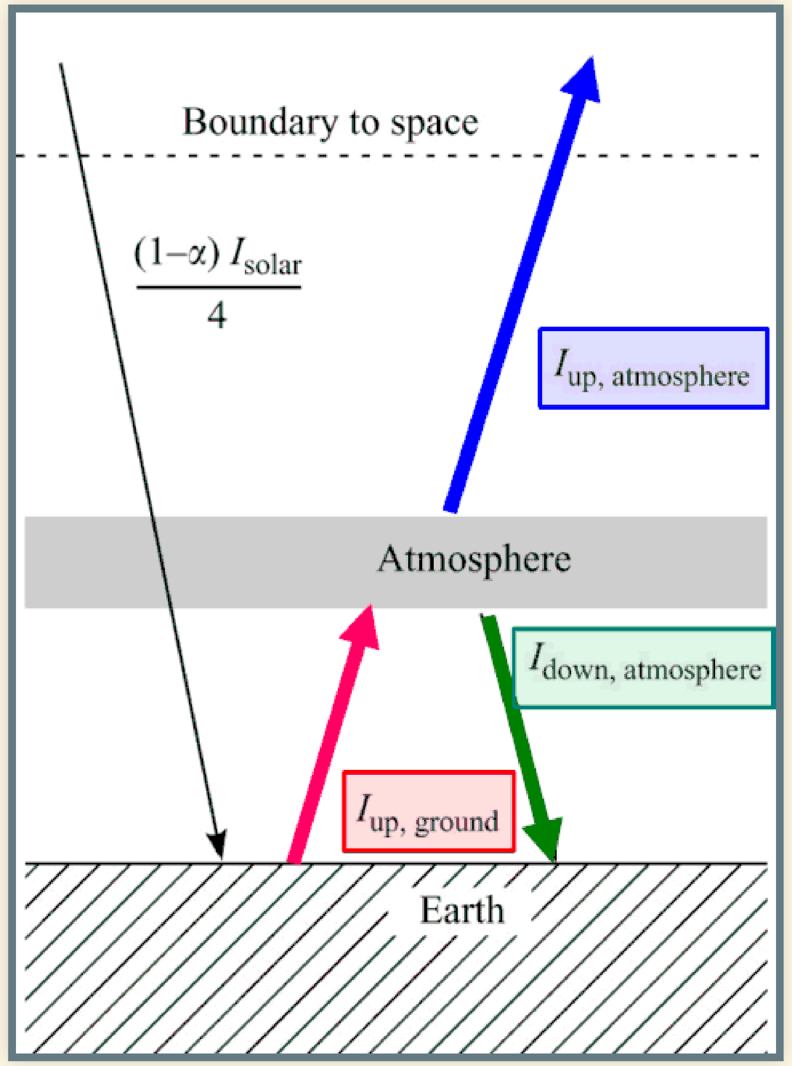
$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

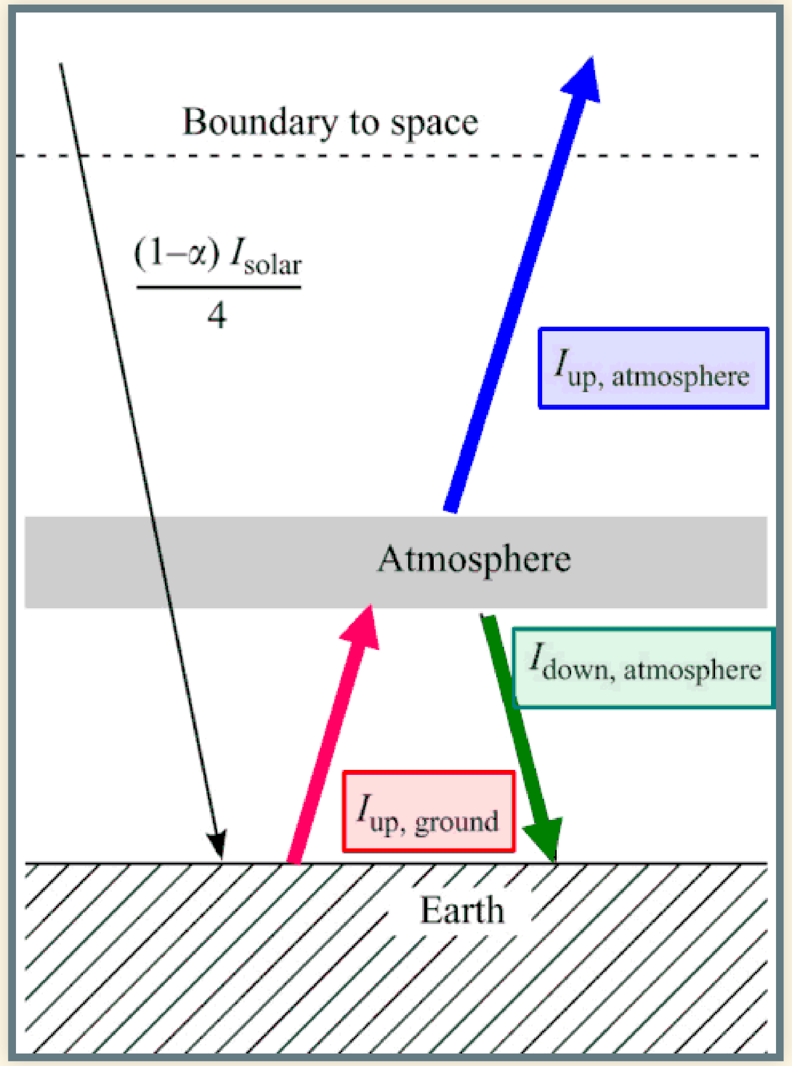
$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$
$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

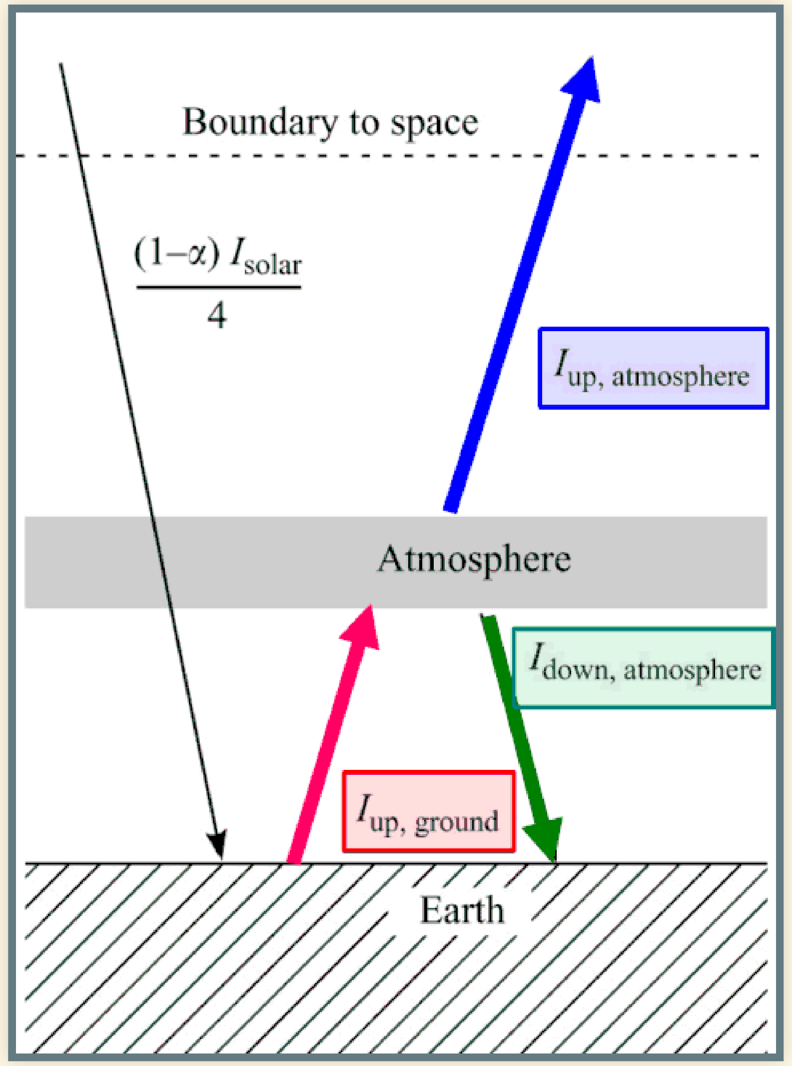
$$
\begin{aligned}
I_{\text{up,ground}} &= I_{\text{up,atm}} + I_{\text{down,atm}} \\
I_{\text{up,atm}} &= I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4 \\
I_{\text{up,ground}} &= \varepsilon\sigma T_{\text{ground}}^4
\end{aligned}
$$



Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$
\begin{aligned}
I_{\text{up,ground}} &= I_{\text{up,atm}} + I_{\text{down,atm}} \\
I_{\text{up,atm}} &= I_{\text{down,atm}} = \varepsilon\sigma T_{\text{atm}}^4 \\
I_{\text{up,ground}} &= \varepsilon\sigma T_{\text{ground}}^4 \\
\varepsilon\sigma T_{\text{ground}}^4 &= 2\varepsilon\sigma T_{\text{atm}}^4
\end{aligned}
$$

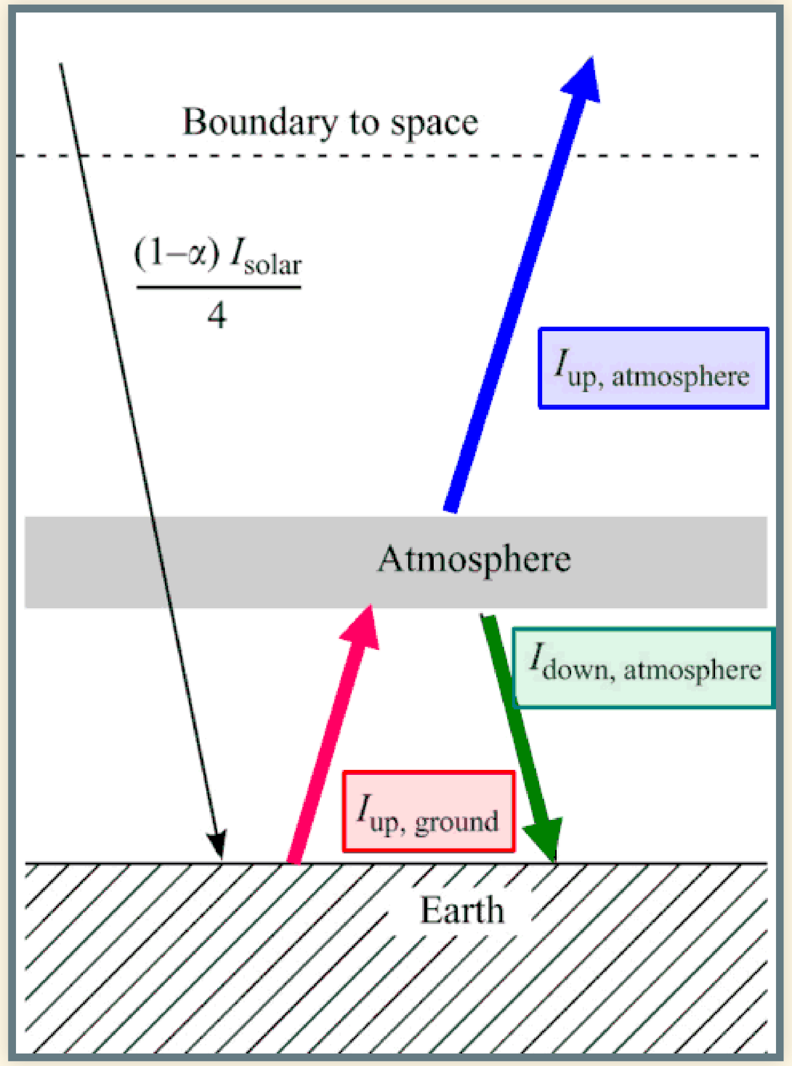


Principles:

- Start at the top.
- For each layer, $\text{Heat}_{\text{out, up}} = \text{Heat}_{\text{out, down}}$
- Each layer balances $\text{Heat}_{\text{in, total}} = \text{Heat}_{\text{out, total}}$
  - Each layer has uniform temperature:
    - The top and bottom of the layer have the same temperature.
    - So the intensity emitted from the top and bottom is the same.
- The bottom layer of the atmosphere tells us $\text{Heat}_{\text{up, ground}}$
- Get ground temperature from $\text{Heat}_{\text{up, ground}}$

Finish the problem

$$\begin{aligned}
\varepsilon\sigma T_{\text{ground}}^4 &= 2\varepsilon\sigma T_{\text{atm}}^4 \\
T_{\text{ground}}^4 &= 2T_{\text{atm}}^4 \\
T_{\text{ground}} &= \sqrt[4]{2}\;T_{\text{atm}} \\
&= 1.19\,T_{\text{atm}}
\end{aligned}$$

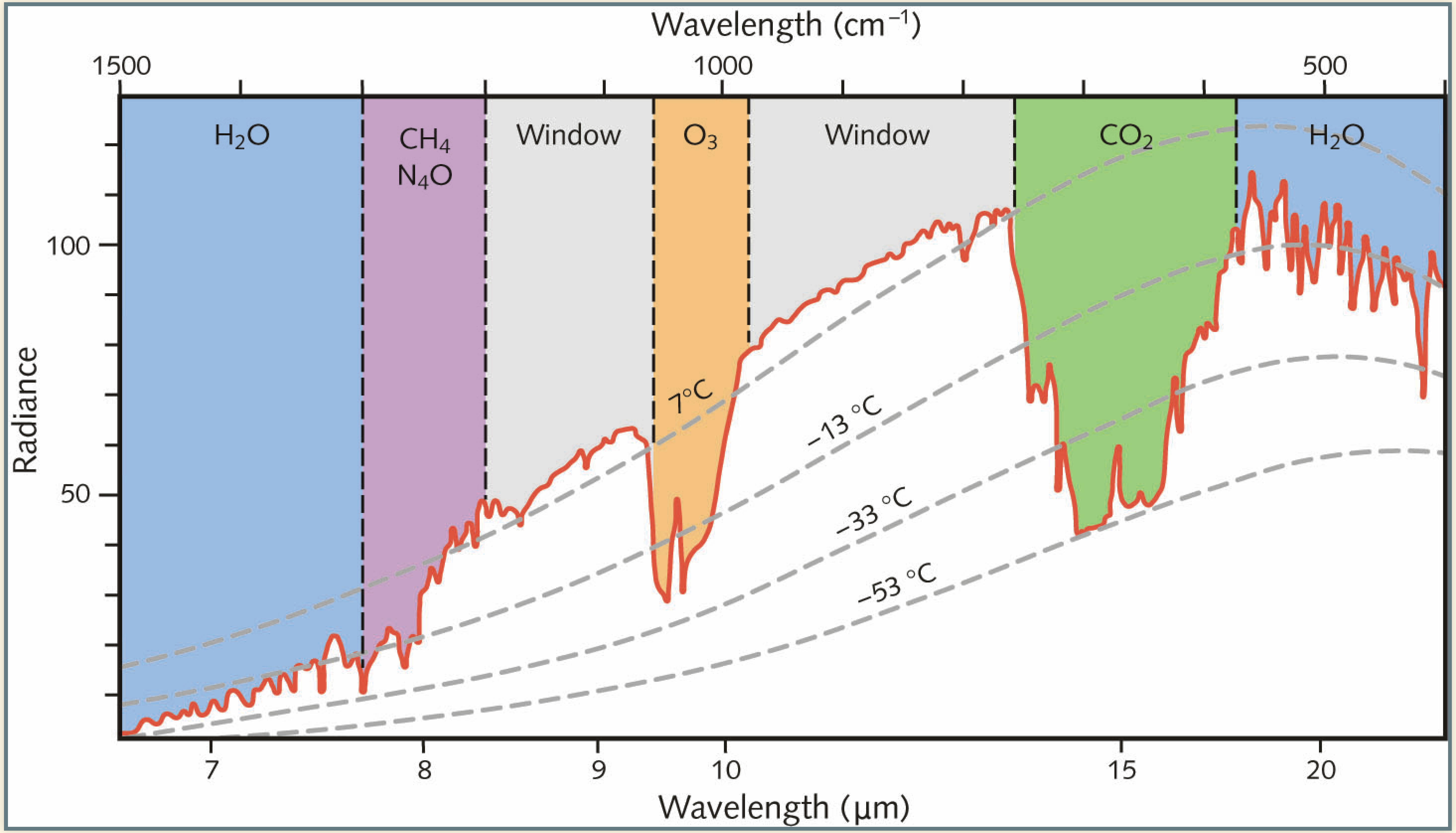


- Skin temp: $T_{\text{atm}} = T_{\text{skin}} = T_{\text{bare rock}} = 254\ K$
- Ground temp (1-layer): $T_{\text{ground}} = \sqrt[4]{2}\,T_{\text{atm}} = 302\ K$
- Difference: $\text{Greenhouse effect} = 48\ K$

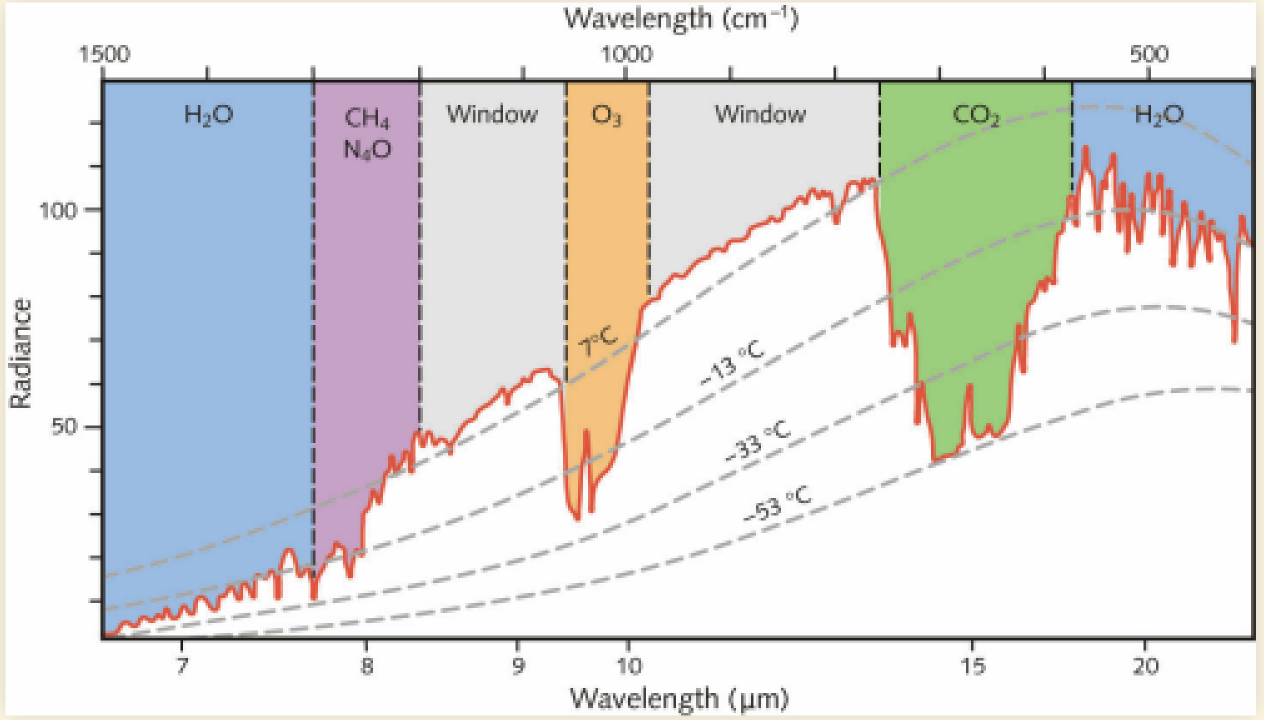
Note: These numbers are slightly different from what's in the book. Don't worry about that.

Greenhouse Gases

Greenhouse Gases



Greenhouse Gases

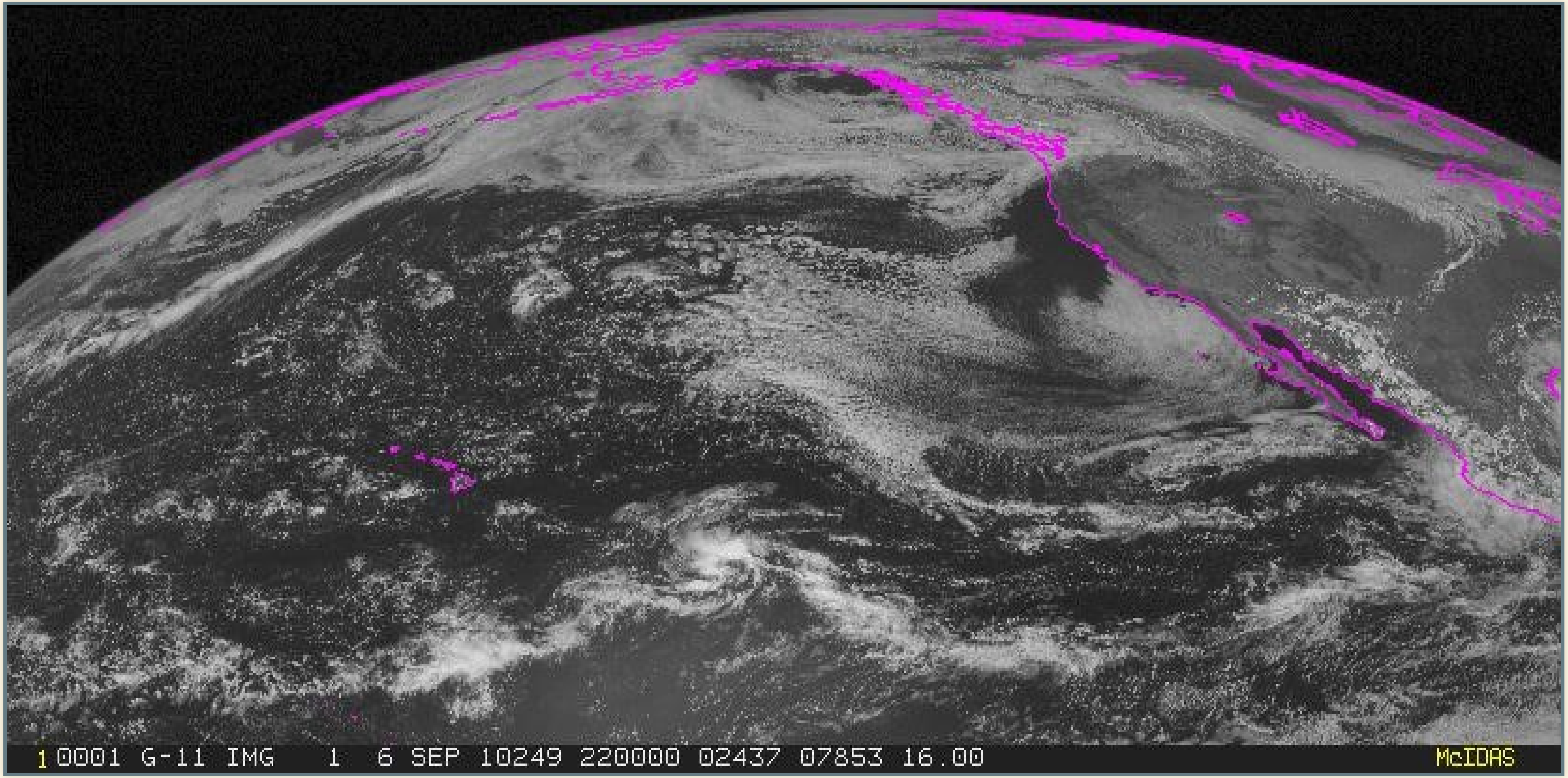


- Brightness: Stefan-Boltzmann law:
  - $I = \varepsilon \sigma T^4$
  - $\varepsilon = 1$

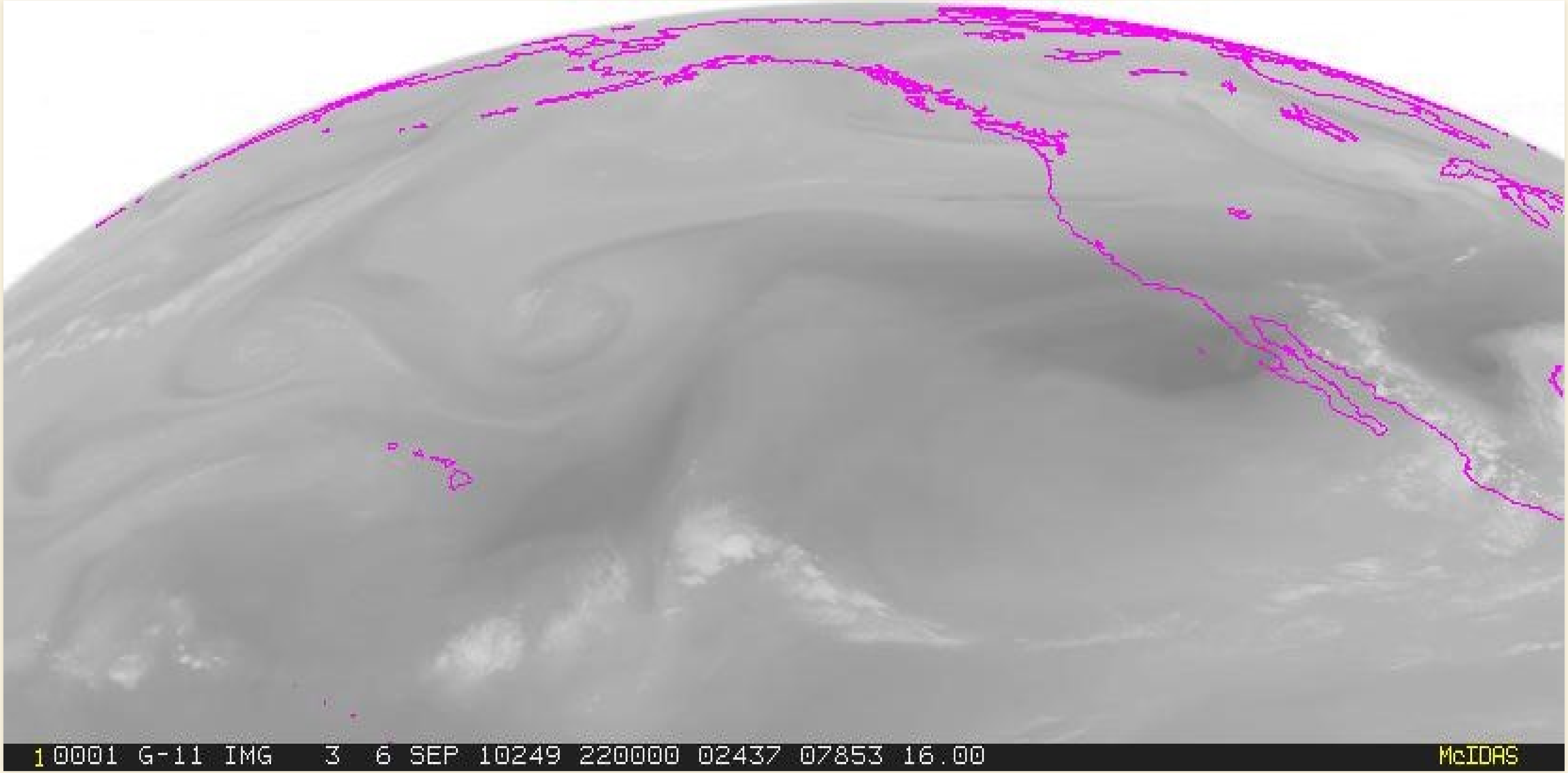
- Brighter = Hotter
- Hotter = closer to ground
  - Satellite can see through atmosphere to low altitude (hot, bright) in “window” region.
  - Satellite can see to middle-troposphere (cold, dimmer) in “water vapor” region
  - Satellite can’t see past top of troposphere (very cold, very dim) in CO_2 region.

Earth Seen by Satellites

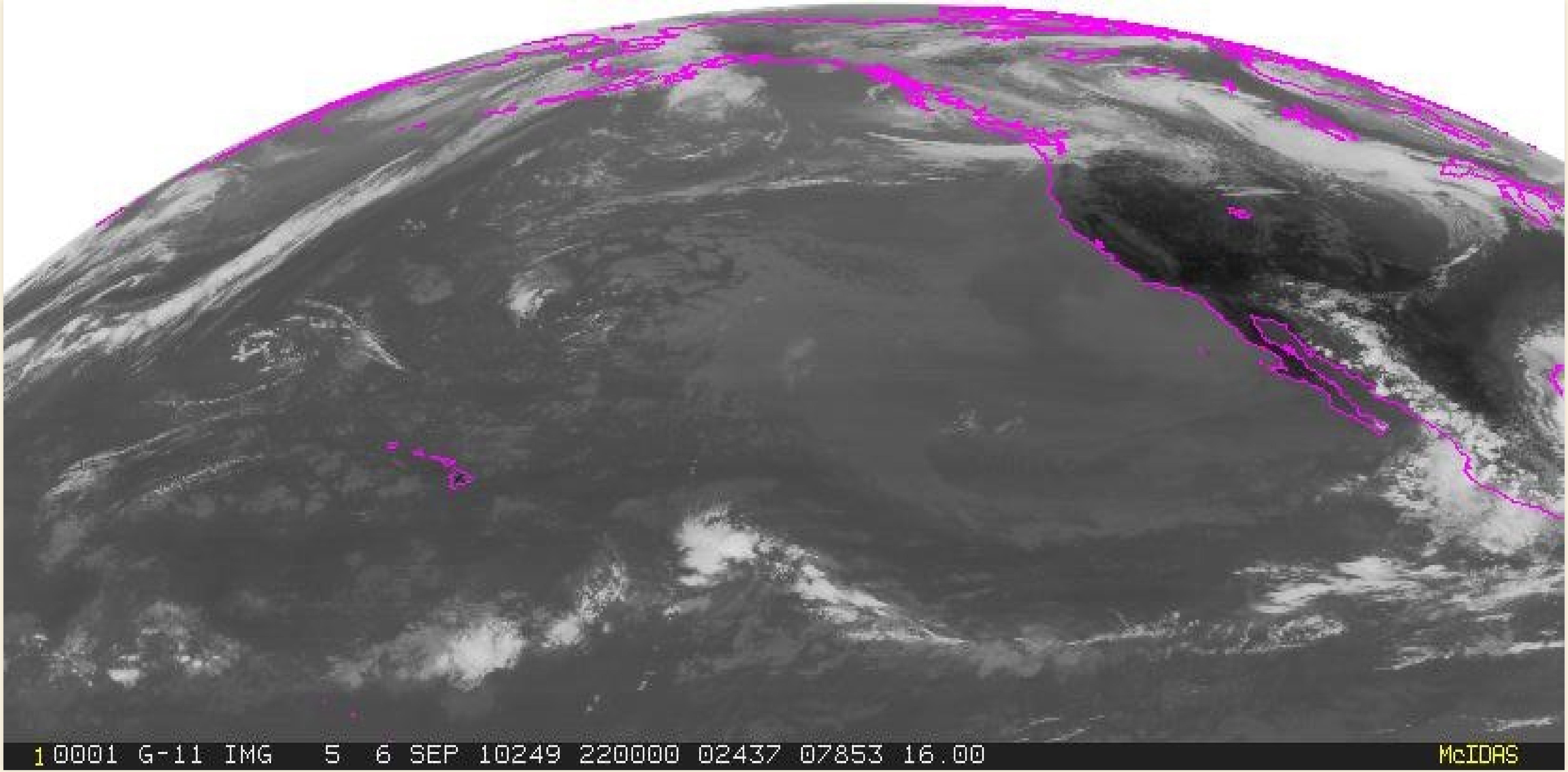
Visible



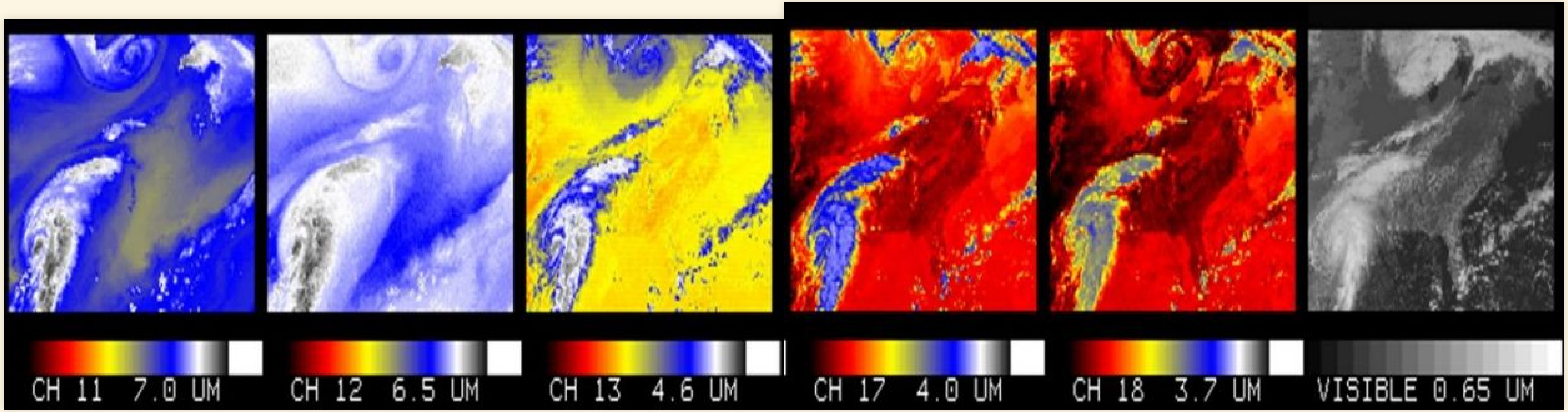
6.8 μm (Water Vapor)



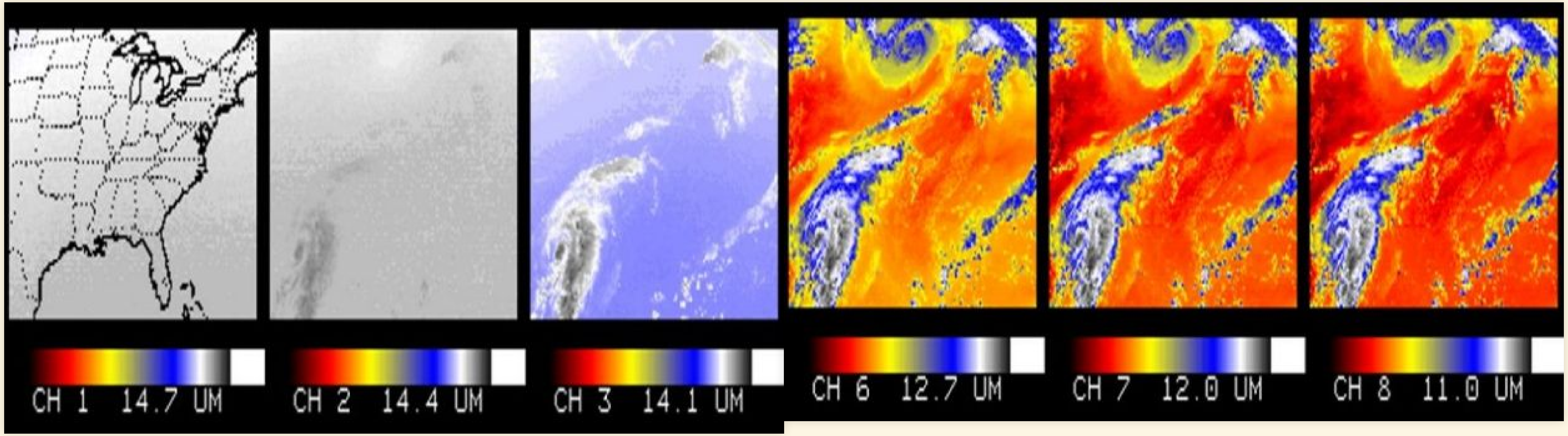
12.0 μm (Window)



Water, Window, Visible



CO_2 peak vs. Window



Terrestrial Planets

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	1350 W/m^2	600 W/m^2	2604 W/m^2
Albedo	0.30	0.17	0.71
$T_{\text{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K

Vocabulary note:

- "radiative temperature"
- "skin temperature"
- "bare rock temperature"

all mean the same thing.

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	1350 W/m^2	600 W/m^2	2604 W/m^2
Albedo	0.30	0.17	0.71
$T_{\text{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K
Difference	7 K	17 K	−414 K

One-layer model works pretty well for Earth.

Not so well for Mars

Terribly for Venus.

Earth, Mars, Venus

	Earth	**Mars**	**Venus**
Solar constant	$1350\ \mathrm{W/m^2}$	$600\ \mathrm{W/m^2}$	$2604\ \mathrm{W/m^2}$
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$T_{\mathrm{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K
Difference	7 K	17 K	-414 K
Atmospheric pressure at surface	1013 mb	6 mb	92,000 mb